The Use of Advanced Technology in South African Agriculture: Insights from selected sub-sectors

Alexis Habiyaremye, Phumzile Ncube, Kiru Sichoongwe and Anele Slater

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DSI/NRF SOUTH AFRICAN RESEARCH CHAIR IN INDUSTRIAL DEVELOPMENT

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Abstract

The use of advanced technologies in South African commercial agriculture has a long history. Digital technologies have been acknowledged as a potentially revolutionary way to boost the efficiency and sustainability of agricultural production systems. The South African agricultural sector is a significant contributor to the country's export earnings, food security and employment. In the era of the fourth industrial revolution (4IR) and other digital technologies, the South African agricultural sector could benefit from more intensive digitalisation, such as precision agriculture and climate smart agri-food systems that balance the shifts in demand preferences and sustainable supply. This study analyses the patterns, drivers, constraints and sustainability implications of advanced technology adoption in the South African agricultural sector. Using in-depth interview data, we generate evidence-based insights into the dynamics of advanced technology adoption and diffusion. We use the 'technology-organisation-environment' and the 'technology acceptance model' to analyse the implications of advanced technology adoption and diffusion for productivity, skills and labour needs in selected agricultural sub-sectors, with a specific emphasis on the citrus production sub-sector.

We find that factors such as perceived usefulness, economies of scale, complementary technological infrastructure and access to finance play an important role in enabling precision agriculture technologies. For the citrus sector, additional factors – such as market requirements and harvest optimisation – appear to be key drivers of automation technology in the packhouses. The economies of scale and the adoption challenges faced by smallholder farmers underscore the importance of coordinated policy and the role of affordable complementary infrastructure in fostering inclusive technology diffusion. Policies aimed at stimulating the adoption and diffusion of precision agriculture technologies will need to factor all these findings into their deliberations, and align them with long-term development strategies.

Keywords: Precision agriculture, AgriTech, 4IR technologies, post-harvest processes

JEL codes: O13, O33, Q12, Q16, Q18

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1. Introduction

The use of advanced technologies in commercial agriculture in South Africa is not a new phenomenon. Farmers have incorporated technologies such as global positioning systems (GPS) and geographic information systems (GIS), along with financial management software, as part of their farming operations as far back as the mid- to late 1990s (Ortmann 2000). In recent years, with increasing demands from export markets, especially with the growth of horticultural exports such as berries and citrus produce, South African agriculture has become even more mechanised, with increasing technological precision through digital technologies in a phenomenon termed the 'industrialisation of freshness' (Cramer and Sender 2019).

Along with other African countries, South Africa is still seeking to increase its industrialisation efforts to foster structural transformation. In that regard, an increase in agricultural productivity is paramount. At the same time, countries in southern Africa are facing extreme weather patterns, including the most recent drought. Food demands have increased due to the rapid growth of the population (Shafi et al. 2019). There is a challenge in meeting the global and national food needs with limited resources (Mumtaz et al. 2017; Shafi et al. 2019). The South African agricultural sector is highly constrained by limited water availability due to the prevalent semi-arid climatic conditions (see e.g. Habiyaremye 2020), which affect yields and productivity. The constraints imposed by the environmental impact of current production methods in the context of climate change imply a central role for innovation and technological transformation of the agricultural production system, because sustainable production expansion cannot be achieved purely through extensive input growth. Agriculture is incorporating several state-of-the-art technologies to increase productivity and cope with the challenges posed by climate change.

Digital innovations such as those found in the fourth industrial revolution (4IR) may enable the growth of productivity in agriculture and in agro-processing in South Africa and, in turn, increase structural transformation. Digital technologies have been acknowledged as a means to boost the efficiency and sustainability of agricultural production systems. Although much of digital technology innovation and early adoption has been pioneered by developed countries, these technologies could have a significant impact on agriculture in developing countries.

The term 4IR includes so-called 'smart' technologies such as artificial intelligence (AI), Blockchain, Internet of Things (IoT), and drones (Stankovic and Neftenov 2020). Where agriculture is concerned, 4IR technologies can be used in various ways. For example, sensors can be used to automatically monitor factors such as temperature, level of moisture in soil and humidity, while drones can be used for tasks such as administering pesticides (Stankovic and Neftenov 2020). This information can be stored and used to determine optimal and efficient management of farming methods, and also for market analysis and logistics (Western Cape Department of Agriculture [WCDoA] 2018). These technologies are often grouped under the name 'precision agriculture' or 'digital agriculture' (see e.g. Kolady et al. 2021 and MacPerson et al. 2022).

In the era of the 4IR and other advanced digital technologies, the transformation of the South African agricultural production system could benefit from more intensive digitalisation, such as precision agriculture, and optimised and climate-smart agri-food systems that balance the shifts in demand preferences and sustainable supply. However, South Africa is still contending with a very high unemployment rate, reaching approximately 32% in the fourth quarter of 2023 (Statistics South Africa [Stats SA] 2024). The increased use of digital technologies may have important implications, especially if the technologies lead to a decrease in staffing requirements.

This study aims to analyse the patterns, drivers, constraints and sustainability implications of advanced technology adoption in the South African agricultural sector. Using in-depth interview data from a small sample of actors in the sector, the study analyses the dynamics of technology adoption and diffusion, as well as their implications for productivity and the skills requirements of staff at the farming level. The interview data was collected from a variety of respondents in different segments of the agricultural sector. Four of the respondents were from the citrus sector. In that regard, the study also includes a separate presentation of the results from the citrus sector.

The rest of this paper is arranged as follows. Section 2 provides a literature overview of the various types of 4IR technologies that are used in the agricultural sector. It also highlights the various advantages and disadvantages related to these technologies. Section 3 discusses the methodology. Section 4 presents the results from the data collection among respondents who were not in the citrus sector in agriculture, while Section 5 presents the results from the respondents in the citrus sector. Section 6 provides a brief discussion of the results, and Section 7 concludes.

2. Literature Review

There are different types of 4IR or digital technologies that are used in agriculture today. These technologies are incorporated in a wide range of activities, from planting all the way to harvesting of crops, and also for the tracking of animals. While various digital technologies are used in agriculture, they can be grouped into what is known as 'precision agriculture' or 'precision farming', which comprises agricultural unmanned aerial vehicles, more commonly known as drones, automated systems for irrigation and pesticide spraying, animal-tracking collars and robotics for harvesting.

The rest of this literature review will outline various precision farming technologies and the drivers of their adoption.

2.1 Precision Agriculture

Precision agriculture has been promoted as being a driver of a technological revolution leading to more economic efficiency and environmental sustainability in the agricultural sector (Kolady et al., 2021, MacPherson et al., 2022). Its perceived advantages are derived from the application of a series of digital technologies and tools that make it particularly suited to maximising farm yield, minimising input costs and optimising farm management, such as imagery and precision spray drones, robots, big data analytics, sensors, IoT, AI, and cloud computing applications (Guan and Grote 2024; Maschewski and Nosthoff 2022; Zuo et al. 2021).

The use of drones in precision agriculture has helped, for example, to more effectively manage pests and diseases, spot and provide image assessments of plant damage, efficiently apply fertilisers and spray pesticides, analyse soil condition (Guan and Grote 2024), and optimise water use (Krishna 2016; Probst et al. 2018; Urbahs and Jonaite 2013; Zuo et al. 2021). Some studies perceive the use of drones in precision agriculture as carrying the potential to considerably reduce agriculture input costs and save billions of dollars (Impey 2014; PWC 2016; Zuo et al. 2021).

While drones have become more powerful over time for the analysis of soil conditions, farmers also use technology such as soil sensors, which are said to have provided significant benefits in real-time analysis of soil conditions such as moisture and root zone conditions (Gebbers and Adamchuk 2010). The consistent analysis of the soil through sensors can also contribute to a heathier environment by optimising the use of potentially harmful chemicals (Shafi et al. 2019).

The use of robotics in agriculture drives the intensification of automation by enabling farmers to monitor individual crops and animals on a constant basis, automatically provide feed (to animals) and fertilisers (to crops), or operate autonomous milking systems (Gabriel and Gandorfer 2023). Robots can also be used for land preparation prior to planting, for actual planting, for autonomous weed control and field scouting, and for harvesting (Oliveira et al. 2021; Shamshiri et al. 2018). Similarly to the soil sensors, where robots are used, there can be more precision with the application of agrochemicals such as fertilisers and pesticides, leading to decreased environmental damage (Manisankar et al. 2022).

IoT applications are used in farming, including the collection of data on rainfall, temperature, humidity, wind speed, soil salinity levels and pest infestation, to help farmers in their real-time decision-making processes to optimise the effectiveness of their activities (Meola 2016). In turn, the data collected through IoT applications becomes useful as input for future decisions (Zhang 2015). IoT-enabled agricultural platforms can also be used to perform informational tasks traditionally executed by agricultural extension agents, and can be used to connect farmers with agricultural machine and drone operators when they wish to perform heavy or specialised agricultural tasks such as soil analysis (Krishnan et al. 2020; Maschewski and Nosthoff 2022).

A common feature shared by these technologies is their high degree of skills intensity and their reliance on specialised digital infrastructure that is required to support their use (Orgunyiola and Gardezi 2022). As a result, their adoption has been slow and uneven, despite their expected benefits, especially in developing countries (Goedde et al. 2021; Kudama et al. 2021). Understanding the dynamics of their diffusion is therefore critical to generating reliable insights into how such technologies are transforming our societies and what policies are most appropriate to steer that evolution in the desired direction (Gabriel and Gandorfer 2022; Ogunyiola and Gardezi 2022).

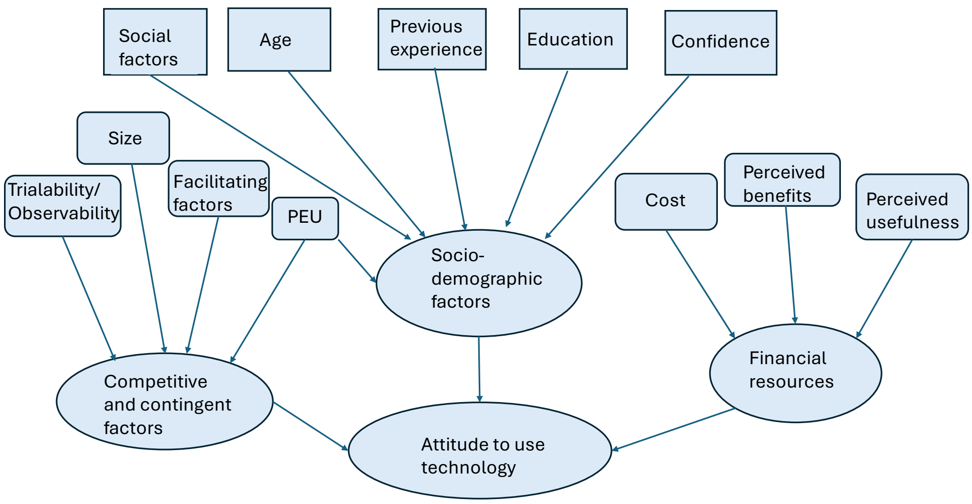
The literature on the adoption determinants of precision agriculture technologies has used various theoretical frameworks and diverse empirical techniques to explain the patterns and rate of adoption among users in different settings. Pierpaoli et al. (2013) propose a conceptual construct based on two main facets of the ex-ante technology acceptance model (TAM) to serve as an encompassing framework to interpret the adoption of precision agriculture technologies by agri-business enterprises. This construct combines the perceived usefulness (PU) of the technology with considerations regarding the perceived ease of use (PEU) as the basis to explain actual adoption behaviour. Perceived usefulness is defined by Davis (1989:320) as “the degree to which a person believes that using a particular system would enhance his or her job performance”, while perceived ease of use is defined as “the degree to which a person believes that using a particular system would be free of effort”.

These constructs portray ex-ante attitudes towards technology adoption as being driven by a wide set of factors that are grouped into three categories: socio-demographic factors, which characterise the would-be adopters, the competitive and contingent factors affecting the adopting agricultural enterprise (such as the farm size, extension services, the market and export structure), and the factors affecting its financial resources, such as the cost of the technology and the perceived benefits. This model has significant overlaps with Rogers' (1995) diffusion of innovation theoretical factors. The theoretical construct provides a schematic summary of the effects of these different factors on the adoption attitude, as shown in Figure 1.

A summary of empirical studies examining the structure of influences on the adoption of precision agriculture technology combining the ex-ante expected drivers and a post-adoption analysis of determinants has revealed a consistent picture, enabling a reliable identification of the main factors affecting adoption decisions: the most important are the size of the adopting farm, the potential for cost reduction or higher profits, the expected total income, land tenure, farmer's level of education, access to extension services and related information sources, as well as the familiarity with computer use (Gabriel and Gandorfer 2023; Pierpaoli et al. 2013). Most adopters identify farm size as the main driver of technology adoption, with larger farms being more likely to adopt precision agriculture technologies. The typical profile of the adopter is an educated farmer with a large farm (bigger than 500 ha) and with a good familiarity with computers, looking for technologies enabling them to face competitive pressure and achieve higher farm profitability (Pierpaoli et al. 2013; Tey and Brindal. 2012). Moreover, Saengavut and Jirasatthumb (2021) contend that small-scale farmers' decision-making processes are also driven by perceived benefits and the younger generation's openness to adopt emerging technologies.

Organisations' facilitating factors include their absorptive capacity (Cohen and Levinthal 1990; Narula 2004; Criscuolo and Narula 2008), their managerial attributes (Aboelmaged 2014; Awa et al. 2017; Rogers 1995), their size and potential economies of scale (Na et al. 2023; Schumpeter 1942), as well as their attitudes towards risk (Awa et al. 2017; Van den Berg and Van der Lingen 2019). Environment factors are related to the competitive pressure faced by the adopting firm, government bureaucracy and the structure of its incentive system (Criscuolo and Narula 2008; Lall 1992; Narula 2004). Policy uncertainty, lack of political support, availability of external financing, as well as weak compatibility with established norms and values may constitute additional exogenous impediments to technology adoption (Foxon and Pearson 2008; Khurana et al. 2023; Narula 2004; Rogers 1995).

Figure 1: Ex-ante factors affecting attitudes to using PA technologies.



Source: Pierpaoli et al. (2013)

Other technology adoption theories such as the 'technology-organisation-environment' (TOE) frameworks, highlight constraints on technology adoption as being categorised into factors related to the characteristics of the technology itself, those related to the adopting organisation and those related to the adoption environment. Technological factors may include aspects such as the perceived benefits of the technology, its complexity and its availability, as well as the presence of corresponding technological infrastructure to enable its deployment (Weil and Broadbent 1998). In the diffusion of innovation theory (Rogers 1995), factors influencing the decision to adopt may be related to its trialability and demonstrability, in addition to cost-benefit and technological complexity considerations. It also entails the availability of technical competence among the personnel that will enable them to run the technological system and keep it in a good state of maintenance and functioning (Abdinnour-Helm et al. 2003; Lin and Lin 2008).

The most common barriers to adoption include costs (adoption costs, resource adaptation costs and regular maintenance expenses), technology relevance, its user friendliness, high skill requirements to operate the system, mistrust of algorithm-driven systems, and adoption risk (McFadden et al. 2023). The digitalisation of agricultural systems can also be hampered by the unavailability of the internet and coverage by mobile digital network infrastructure, the cost of internet connection devices and data (Aguera et al. 2020). The adoption of IoT technologies may also be hampered by their reliance on sophisticated cloud computing infrastructure and digital platforms dominated by powerful corporations with the potential to use cloud monopoly or oligopolistic control structures that leave farmers at their mercy (Maschewski and Nosthoff 2022). It also pushes farmers to changing their epistemological paradigms as they continuously adapt to the increasing skills requirements imposed by the need to use these digital systems in their production (Ogunyiola and Gardezi 2022). The next section presents the methodology used in the study.

3. Empirical Methodology

This paper uses primary data in a qualitative format. The data was collected through 12 online interviews held in South Africa between August and October 2023. The data was collected from a range of players in the South African agriculture landscape. The goal of the data collection was to understand the processes involved in innovation and the adoption of the most recent 'smart' technologies in South African agriculture.

During the scoping exercise used to identify study participants, we targeted both the users of advanced technology in agriculture, in the form of farmers and agribusinesses, and the suppliers of these technologies. This was done to understand the demand-side factors affecting the decisions made by farmers and agribusiness groups to acquire and use advanced technology in their operations. From the suppliers, we sought to ascertain what drove their supply dynamic in the South African agriculture landscape, and what they understood to be the reasons for their customers' adoption of advanced technologies for their farming operations.

This study employed a cross-sectional survey design and a non-probabilistic snowball sampling approach. Potential respondents were identified through internet scoping research. From those who agreed to participate in the study, we requested referrals to other potential study participants. This technique depends on the idea that study participants of the target population are embedded in social networks of other players with similar characteristics who can be recommended to researchers (TenHouten 2017). This technique is frequently employed in qualitative research (Naderifar et al. 2017).

Naderifar et al. (2017) note that the snowball approach is useful when targeting populations that are not easily accessible. The approach was used in this study because it is difficult to find farmers through internet searches, as many of them do not have websites or online profiles. While some large farming groups may have websites, not all of them who have this. Furthermore, not many of those whose contact details we were able to find on the internet were willing to participate in the study. In that regard, we requested referrals to other willing participants from those whom we had successfully secured interviews.

The interviews were semi-structured and covered issues such as the use of advanced technologies in the businesses, the drivers of the adoption (or lack thereof) of the advanced technologies, the types of skills training needed to prepare their workforce for changing skills needs in the production and handling systems, and the costs, benefits and obstacles of investing in advanced technologies.

We eventually interviewed 12 participants, made up of fruit, crop and livestock farmers, industry associations, government departments and technology suppliers. The participants were notified of the anonymous nature of the interviews. In that regard, the respondents are not identified in any way in the study. The breakdown of the respondents is found in Table 1.

Table 1: Interview respondents by type

Respondent type	**Number**
Farmers	4
Packhouse	1
Industry association	4
Government department	1
Technology supplier	1
Other stakeholder	1

The data analysis sought to identify the technology that was adopted by the respondents and to analyse the drivers of technology using the TAM and TOE frameworks of technology adoption.

A key limitation of the study is the relatively low response rate. Part of this is related to the difficulty of finding farmers or farmer groups willing to participate. However, we were able to mitigate this by speaking to industry associations covering a wide array of sectors (fruit, commodity crops and other agribusinesses) who were able to provide a broad outlook of their members. Furthermore, four of the respondents were from the citrus sector. The analysis therefore includes a case study of advanced technology adoption in the citrus sector.

4. Use, Enablers, Constraints and Effects of Advanced Technology in SA Agriculture

This section provides a description of the technology used, drivers of and constraints on technology adoption, and the effects of adoption on factors such as skills and employment.

4.1 Description of the Technology Used in Agriculture

The main types of advanced technologies include those that provide automation of activities or digital solutions. In poultry farming, poultry houses are equipped with automated systems that enable the farm manager to take action immediately without any delay (Interview, 12 September 2023). However, some farmers used them as surveillance technology on the farm to monitor security (Interview, 12 September 2023). Furthermore, for larger environments such as greenhouses, farmers tend to adapt and innovate with the tools they have.

Another technology that has revolutionised farming practices is drones. For instance, the use of drones has been of great help to both commercial and small-scale farmers. Drones are also used for field assessments for advisory services, such as assessing soil and plant health (Interview, 23 October 2023), and also for administering pesticides.

A digital technology provider to the agricultural sector mentioned that they use satellite imagery to provide services that include soil classification by examining the physical properties of the soil, and soil chemical analysis, which involves taking soil samples and sending them to the laboratory for geospatial data processing (Interview, 23 October 2023). This data is then used for variable rate application or variable rate corrections in the field, using geospatial tools that are available to farmers. Furthermore, analyses of the biological aspects of soil include examining the micro-organisms present in the soil, assessing their intensity, and finding ways to increase them. The focus is on carbon credits, soil health and regenerative agriculture, which are beneficial for farmers looking to enhance their understanding of soil and improve their crop yields.

The service provider also conducts leaf sampling and foliar analysis. These samples are tested in laboratories for carbohydrates in plants and to monitor their status during certain phenological stages. This process allows soil mapping and access to specific soil maps, and also includes water analysis. This type of data, provided by precision planting technology enabled by computer vision and sensors, is used to identify areas with high potential and to plant more seeds and apply more fertiliser there. This helps to use the soil potential efficiently.

Other software technologies adopted in farming applications are 'fieldmargin' and 'FieldView', which help simplify the work (Interview, 23 October 2023). 'fieldmargin' is farm management software that helps farmers to map their fields and do real-time monitoring of weather data and satellite imagery. 'FieldView' is a precision agriculture platform that provides farmers with advanced data visualisation and predictive analytics to maximise production and crop yields. These applications assist in overlaying aspects such as soil mapping and plant data to make the work more efficient.

A grain farmer stated that all the farming equipment that they use, including the large tractors that are used for planting, are equipped with GPS and soil maps (Interview, 27 October 2023). Most farmers in the grain industry use GPS guidance technology. The GPS guidance optimises the planting of seeds and application of fertilisers. To further optimise the digitalisation of the tractors, the farmer mentioned that the tractors are set up with auto-steering technology. With this technology, the tractor operator can let go of the steering wheel and the tractor can drive itself based on data inputted into the GPS guidance system.

In addition, all the tractors can connect with one another, an aspect that is enabled by IoT, which allows for remote monitoring of irrigation and planting (Interview, 27 October 2023). Grain farmers' focus in terms of crop development is moving towards more regenerative practices, although this has not het been achieved. The grain farmer stated, that due to the nature of the soils, it is not yet possible for them to adopt completely regenerative agriculture. However, technology plays a significant role in helping farmers achieve their objectives.

Finally, the technologies adopted by players in the agricultural sector can also be biological. These include breeding of seeds and livestock for optimal growth in their environment. In mixed scall-scale farming, specifically on the stud side, genetics and DNA testing are used to improve cattle breeds (Interview, 27 October 2023). Beehives also are used for pollination and monitoring with AI systems and cameras to count bees in orchards (Interview, 12 October 2023). This is a common technology used by grain farmers. Since the year 2000, there has been significant progress in these areas, particularly in seed breeding. These advancements have more than doubled the yields of crops and livestock.

4.2 Drivers of Technology Use

In some respects, technology use among farmers is influenced by the extensive and ongoing use of the technology by other farmers. This was particularly the case for small-scale farmers. A reason for this is the ease with which farmers may consult one another for further guidance and ideas while using the technology (Interview, 15 August 2023). However, a lack of technical skills and expertise may sometimes make farmers reluctant to adopt and use technology. The intricacy of new technologies may overwhelm them, or they may doubt their capacity to use them efficiently (Interview, 15 August 2023).

Technology adoption was also influenced by the related costs. Before the farmers adopted a technology, they considered competitive advantage and cost savings, understanding that the adopted technology can enhance productivity and reduce risks. For instance, low-cost equipment may encourage farmers to use the new technology, particularly on smallholder farms. No matter how well liked a technology may be, it is unlikely to be implemented if the acquisition cost is too high (Interviews, 15 August 2023; 13 October 2023; 27 October 2023). Furthermore, farmers take into consideration profitability – the long-term financial sustainability of technology use. Farmers might not have access to critical information about how profitable technologies are, and their usage of technology will be greatly affected by this. Profitable technology application will raise farmers' well-being, which is primarily determined by productivity and income (Interview, 23 October 2023).

Farmers also noted that they realised improvements in their crop management and efficient use of resources allocated after adopting precision agriculture technologies, thus validating the TAM’s emphasis on perceived usefulness (Pierpaoli et al. 2013).

Finally, value chains may have a significant influence on how farmers use technology via vertical coordination and spillover effects. Technology use within a value chain is contingent upon the holdup opportunities inside the value chain, and can occur even in technology markets (Interview, 20 October 2023).

4.3 Constraints on Technology Adoption

The adoption of 4IR by small-scale farmers is hampered by the following factors: financial constraints, size of the farmer’s operations and their socioeconomic characteristics, data costs, cost of technology, inadequate infrastructure in place, anticipated benefits of the technology, the export market, market participation, generational divide and crop dynamics.

The lack of access to financial services is one fundamental barrier preventing these agricultural technologies from being widely adopted. Financial constraints discourage farmers from investing in agricultural technologies because they limit their ability to obtain finance and prevent them from engaging in high-yield farming practices. Also, the size of the farmer’s operations and socioeconomic characteristics do matter when it comes to how quickly technology is adopted. For example, compared to their counterparts, large and wealthy farmers can more easily adopt technology.

Similarly, data costs related to accessing the internet are a major obstacle when it comes to adoption. For instance, if a farmer has IOT items in their greenhouse, the IOT sensors need another computer to read and communicate the results. In addition, software and user interfaces are extremely important and intricate systems, and require communication with one another. This process requires enough stable data. Furthermore, farmers have acknowledged the challenges they face while adopting new technologies, including availability and affordability. When the technology is expensive, most farmers might not adopt it. Adoption is still significantly hampered by the high cost of technology. Pierpaoli et al. (2013) provide theoretical evidence for this that suggests that financial resources – that is, low cost – have a positive effect on the adoption of technology.

For the same reasons, innovation diffusion theory (IDT) aligns with this, emphasising that the adoption of technology is primarily determined by five fundamental stages, which are knowledge, persuasion, decision, implementation and confirmation. The process of deciding on adopting begins with familiarity with the technology and continues until the stage of confirmation (Kocak et al. 2013). Each successive stage in the process is necessary for the next stage to occur. The decision stage is when farmers decide whether to adopt or reject the technology (Kitchen and Panopoulos 2010). One of the many obstacles is the lack of infrastructure to accommodate smallholder farmers' demands in terms of coverage, scale and human capital requirements.

A further barrier relates to the benefit and/or reward (long-term profitability) that a farmer will receive. A farmer will embrace new technologies and advance with them if there is a corresponding benefit and/or reward (return on investment) in place. The likelihood of adopting any given technique increases when a farmer is guaranteed returns. The export market, with its strict standards, is another major factor influencing farmers' adoption of technology. For farmers supplying to the export market, the competition is both local and global. Thus, technology becomes one of the tools for international competition, providing farmers with a competitive advantage.

Market participation also plays a crucial role, since it affects the gross margins due to increased output, which in turn affects how technology is adopted. Market participation therefore has a direct influence on technology adoption. Another aspect to consider that influences the uptake of technology is the generational divide. Compared to older farmers, many younger farmers use technology in their farming operations. Finally, technology adoption for annual crops occurs more quickly than for perennial crops. The reason for this is that annual crops generate greater revenue.

To mitigate the constraints, one of the respondents stated that government departments and agencies, such as the Agricultural Research Council (ARC) and the Department of Science and Innovation (DSI), have introduced innovative solutions that are being implemented through the Council for Science and Industrial Research (CSIR). One such solution is the use of drones for field assessment and advisory services. This is a positive development as it helps to overcome the challenge of the limited number of extension practitioners, who cannot physically reach all farming communities.

4.4 Effects of Technology Use on Employment, Skills, Production/Productivity and Sustainability

In the poultry sector, certain farm tasks and even jobs have become obsolete because of the increased use of technology and automation in the industry. As a result, jobs are threatened by the forces of automation and technology. Also, in recent decades the blueberry industry has seen a significant transformation due to the introduction of new technology and scientific advances. However, jobs in the blueberry sector have not been displaced because of technology use since there are not many automated fruit farming operations. Furthermore, the use of robotics and AI information in grain harvesting has not created any jobs.

When it comes to skills sets, the poultry industry attracts people with the necessary skills to use the technology. Subsequently, matching skills to the demands of the technology presents little difficulty. The industry has changed significantly over time because of the technologies being used, leading to a sharp increase in productivity. With regard to the blueberry sector, the skill level of farm labourers remains significant in determining the effective adoption and usage of novel technologies. A lack of competent skills could cause adoption to lag, which would have a big impact on how the technology is used.

In other areas of the agricultural sector, some farmers are equipped to fully utilise modern technologies in terms of skill requirements. On the one hand, some farmers now need to retrain or reskill to keep their jobs from becoming obsolete due to the new technologies. Unlike their younger counterparts, who find technology easy to use, most older farmers lack the necessary skills and abilities to use it. A variety of curricula are offered by the government department with the goal of developing the skills of farmers. In actuality, the level of chief directorate has a full division dedicated to agricultural education and training.

The Comprehensive Agricultural Support Programme is one such scheme that allocates 10% of its budget to skills development. This implies that 10% of the financing for farmers and their management teams on that farm has to go towards developing their skills and capacities, regardless of the needs analysis or assessment that needs to be done. With this strategy, the use of technology is supported, productivity is increased, and job losses are prevented from becoming the norm due to technology use. This adds value for the farmer and improves profitability, efficiency and sustainability.

Nonetheless, the scope and output of agricultural productivity have increased due to technological advancements in the field. Not only has farming become more profitable and sustainable, but it has also significantly decreased the amount of manual labour that many farmers need to perform. Lastly, utilising technology allows farmers to fully optimise their operations, leading to increased efficiency and output, and guaranteeing sustainability.

5. The Use of Advanced Technologies in the Citrus Farming Sub-sector

This section presents the findings from the analysis of advanced technology in the citrus sub-sector. The results in this section include insights from respondents in different parts of the citrus industry. While the previous section was based on insights from respondents in various industries, this section uses the citrus industry as a case study for a more in-depth analysis of advanced technology in agriculture. The respondents included representatives from a vertically integrated citrus business, which includes nurseries, citrus farms, packhouses and marketing, and representatives from industry associations.

The analysis of the use of advanced technology in the citrus industry can be split into pre-harvest and post-harvest components. The pre-harvest analysis includes technology used in nurseries and in farming. The post-harvest component of the analysis comprises mainly an analysis of the technology used in packhouses.

As highlighted in Section 2, the main types of advanced technology that are used in agriculture include precision agriculture, robotics, regenerative agriculture and climate-smart agriculture. Precision agriculture consists of various tools such as sensors, drones and GPS guidance systems, along with spatial analysis such as satellite imagery. Adaptable mechanisation and robotics include the use of robots for tasks such as weed control, field scouting, and harvesting and packing. Biotechnology advancements include gene editing, which is used for plant breeding.

This section begins by outlining the technology used in pre-harvest parts of citrus farming and the drivers of this usage, followed by the analysis of post-harvest usage of advanced technology.

The analysis shows that, while there have been advances in technology in farming, especially from a monitoring perspective, there is still very little automation. The need for human intervention remains relatively strong. By contrast, there is far more pervasive penetration of advanced technology in the packhouses, where many functions have been automated.

5.1 Advanced Technology Usage and Drivers in the Citrus Farming Industry

5.1.1 Pre-harvest use of advanced technology in citrus farming

Advances in precision agriculture were found in the citrus farming industry. One of the key forms of advanced technology in citrus farming identified by the respondents is the integrated farm management software known as ‘FarmNode’. ‘FarmNode’ consists of various modules, including irrigation monitoring, pest management and fertiliser management.

The irrigation module consists of soil probes known as capacitance probes, and in some cases tensiometers, that are used to record soil moisture levels. The probes are continuously logging soil moisture data and this data is saved in the cloud. The information is collected by monitoring stations in every block. The moisture data in the monitoring stations is entered into tablets by scouts, and this information is used to make decisions on how much irrigation is required. It is not an automated process, as human intervention is still required to interpret and investigate the accuracy of the information collected from the monitoring stations. When a reading reflects that the soil is too moist or too dry, the scouts must physically assess the soil in the area that has been identified as being problematic, determine the extent of the issue and then decide on the intervention required to rectify the problem (Interview, 12 October 2023). The irrigation can then be set and controlled remotely through computer software.

The pest management module uses information gathered by the scouts to determine the type of pests, the size of the area affected by them and which chemicals to apply, and then calculates how much of these chemicals should be applied to eradicate the pests. As with the irrigation module, the pest management module requires human intervention in the collection and interpretation of the information provided by the software. The module allows users to achieve the targeted application of chemicals in the correct doses.

The fertiliser module is similar to the pest management one, but keeps track of fertiliser applications. Fertiliser usage is uploaded to the system, which then tracks the amount of fertiliser used in each block of trees. Finally, the software is also integrated with the packhouses, as they upload crop estimates to the system. The packhouse integration allows the packhouses to plan their packing programmes.

Another form of precision agriculture used in the citrus farming industry that was identified is the use of temperature control systems in the nursery tunnels where seedlings are produced (Interview, 14 August 2023; Interview, 12 October 2023). These systems constantly monitor temperature in the tunnels and make adjustments when needed. For example, when temperatures rise above a pre-determined level they spray water, and when they drop too low the temperature is adjusted. This specific technology led to the respondents producing better quality plans, preventing loss due to extreme temperatures, and allowing the year-round production of seedlings.

Other precision agriculture tools such as drones, GPS guidance systems and spatial analysis are also used in the citrus farming industry. Respondents noted that there have been advancements, with some companies offering plant and orchard monitoring services using drones. One respondent stated that some farmers use drones for the remote monitoring of their farm operations (Interview, 20 October 2023). Another respondent stated that their business had run trials with drones and the associated software. Similarly, most of the respondents mentioned having trialled the use of satellite imagery for their operations. However, neither of these technologies had been taken up in their businesses because they were too costly or were not scalable for their businesses (Interview, 12 October 2023).

GPS guidance systems are fitted onto tractors, using software known as 'Farm Trace', are used to track where certain work has been done, such as spraying and sowing (Interview, 12 October 2023). Among other functions, the tracking technology provided by Farm Trace and placed on the tractors allows farmers to see, for example, where chemicals are being applied (Interview, 12 October 2023). They can then use this information with the pest management information gathered by scouts to ascertain whether interventions have been successful.

From an adaptable mechanisation perspective, the respondents identified Bluetooth callipers and hydraulic pruning shears. Bluetooth callipers measure the size of the fruit and send the information to a spreadsheet (Interview, 14 August 2023). A respondent stated that there have been further advances in the technology in the form of sensors that are placed on the fruit and are constantly measuring and taking photos of the plant (Interview, 14 August 2023). The Bluetooth callipers are a cheaper option, however, and are better and less time-consuming than physical measurement and capturing.

According to one of the respondents, hydraulic pruning shears have replaced pruning by hand (Interview, 12 October 2023). The hydraulic pruning shears allow the worker to press a button and the shears cut whatever needs to be pruned. With this technology, it has increased the productivity of the workers, who are able to prune up to 200 trees per day compared to 100 trees when pruned by hand (Interview, 12 October 2023). Although these technologies are not as advanced as some of the precision agriculture tools, they have still resulted in positive benefits for the respondents in terms of higher productivity of the workers, and less time-consuming but more accurate measurement.

5.1.2 Drivers of pre-harvest technology adoption

As mentioned in Section 2, technology adoption theories such as the TOE framework identify three factors that explain why companies do or do not adopt certain technologies: the characteristics of the technology, the characteristics of the adopting organisation and environmental factors faced by the adopting firm. Based on the interviews with respondents from the citrus industry, the main reasons for the adoption of the technologies for pre-harvest activities relate mainly to technological and environmental factors.

The first reason for technology adoption for pre-harvest activities such as irrigation and pest management is that it reduces the time spent on collecting and capturing the information from plant and soil monitoring, and also allows for decisions to be made timely. This is related to the characteristics of the technology, which encompass the perceived benefits of the technology and the technical competence of the staff (Rogers 1995; Weill and Broadbent 1998). For example, the collection of moisture information previously was a two-step process. The first step was the manual collection of the data, which would take time. The second step was entering the information collected by all the scouts into the system. This has now been reduced to one step through the Farm Node system because the scouts enter the information into a table that captures it and saves it on the system in real time, saving on time and allowing for quicker decision-making not only in relation to irrigation, but also to pest management and fertiliser application (Interview, 14 August 2023; Interview, 12 October 2023).

The remaining two reasons for adopting advanced technologies in citrus farming are related to the environmental factors faced by the firms, and the fact that the higher supply of citrus in the country over the years, in addition to supplying the export market, has increased competition. The competitive pressure faced by a firm therefore could lead to it adopting more technology (Criscuolo and Narula 2008). The quality of the fruit in terms of size, fruit specifications, taste and so on has become a very important aspect to compete effectively in the market. For example, there are specifications – such as the peel thickness, the ease with which one can peel the fruit and the taste – which are determined by irrigation and fertiliser application (Interview, 14 August 2023). Close monitoring of both irrigation and fertiliser application allows for adjustments to be made when the fruit are still young to meet the quality standards set by the clients.

The final reason for the adoption of advanced technologies at the pre-harvest level is that competing in the export market is information-intensive. The main environmental factors to be considered in this case are an increased level of bureaucracy and the need to adhere to the standards of customers (Lall 1992; Narula 2004). Customers in the export market require their suppliers to have certifications such as the Global Good Agricultural Practice (Global GAP), 'Farming for the Future' and Rainforest Alliance. These certifications require regular audits that collect information on water usage, fertiliser applications, and chemical or pesticide usage to determine whether the suppliers are farming responsibly and in a sustainable manner (Interview, 12 October 2023). The digital technologies used in the collection of the irrigation, fertiliser and chemical application data provide a means to collect more of the required data in a shorter space of time.

In the next sub-section we identify and analyse the adoption of advanced technologies in the post-harvest activities in citrus farming.

5.1.3 Post-harvest use of advanced technology in citrus farming

The main post-harvest activity is the packaging of the fruits, which often takes places in packhouses. The interviews revealed the main type of advanced post-harvest technology is advanced mechanisation, with the packhouses being equipped with machinery that operates autonomously. According to one of the respondents, the packhouses are where one will find the most advanced technology, even though there are varying degrees of automation (Interview, 12 October 2023).

The first stage of the packhouse line, the auto-tipper, was highlighted as having advanced technology (Interview, 11 October 2023). From harvest, the fruit is placed into bins, loaded onto a machine that automatically tips the fruit over the automatic wet line. In the wet line, the fruit is cleaned, sanitised and protected with post-harvest chemicals. They are then dried and further protected by a wax system.

The next stage is the grading system (Interview, 14 August 2023; Interview, 11 October 2023). The automated grading system consists of a camera that takes about 26 photos per fruit. Through the numerous photos taken of each fruit, the machine allocates it to a class depending on its size, appearance (including colour and the presence of markings such as blemishes) and shape (whether it is more oblong or round). The grading system determines whether the fruit meets the requirement for the local fruit market or the export market and then places it in the correct outlet depending on its classification. This grading system rapidly scans and analyses the fruit to ensure that only fruit that meet the requirements and criteria of the client are packed for said client.

The final stage is the outlet system. This is where the fruits are packaged according to customer needs and requirements. They are either packaged into different sized boxes (10 kg or 50 kg boxes), depending on customer requirements, or are 'place-packed' into a box that a client (for example, a supermarket) will put directly into the fruit section without being unpacked or repacked.

The grading and sorting system is programmed with the parameters required by each specific destination (e.g. Europe or the USA), the specific client, the labels, grade and quality of the fruit required in each destination, and so on. A respondent said that, depending on the size, appearance and colour of the fruit, the machine decides whether the fruit can go to China or Europe, for example, which box it should be in and which size (Interview, 11 October 2023). With this information, the system can package and label the fruit correctly before it is palletised and moved by a trolley onto a rack, ready for being dispatched to clients.

5.1.4 Drivers of post-harvest technology adoption

The key argument for incorporating any form of advanced technology, particularly in the packhouses, is to be able to sustain the throughput required (high volumes) while also meeting the high levels of complexity required (especially) by export customers (Interview, 11 October 2023). In this regard, technology adoption is related to organisational factors and also factors related to the technology itself, particularly the need for significant scale to push the volumes required within a specific period. The advanced technology in packhouses allows citrus producers to get through the volumes of fruit required, with varying client requirements, in a short space of time. The automated grading system significantly cuts down the amount of time spent sorting the fruit for different markets. It is said to be able to grade approximately 5 000 tons of fruit per week, which is a much higher volume than what the throughput would be if it were done manually. Previously, grading was done by eye. A respondent commented that it would be "impossible" to grade the fruit by eye for blemishes and phytosanitary issues at the required volumes and levels of complexity.

Given that fruit is perishable, it is important to complete its packing and packaging, which includes grading and ensuring that the correct quality goes to each customer, in a short space of time. One of the respondents stated that their biggest constraint was moving large enough volumes through the packhouse, grading the fruit and packing it within approximately a week of picking.

With more export markets opening up and becoming increasingly diverse, there is an increased need to include advanced technology that can pack the fruit in the required amount of time while meeting the different requirements of the various export markets. This suggests that post-harvest technology adoption is also due to environmental factors. For example, a respondent stated that the regulations and requirements to export to Europe are different from those of the UK, which are different from those in Asia, the Middle East and the USA, and so on (Interview, 11 October 2023). In this regard, a citrus producer who supplies to multiple export destinations needs to bring in technology to ensure the necessary throughput out of the packhouse in a specific period. A respondent stated that the automated system allows for more complexity and utilises less space (Interview, 11 October 2023).

A respondent noted that the automation of the packhouse itself is not a requirement of their customers (Interview, 11 October 2023). However, they use the automation to allow them to comply with their throughput targets, their capacity and the complex requirements of the different clients over a specified period. The respondents noted that technology assists them to ensure that non-qualified fruit are taken out of the system and that only fruit that qualify to be sold to specific customers are left.

While this section has highlighted the reasons for the use of advanced technology, not all farmers adopt these technologies. A key reason for the lack of adoption of advanced technologies is that the cost can be very high and that many farmers are unable to afford it. This suggests that, for some farmers, the technological factors related to the cost of the equipment hinder them from adopting the technologies, in spite of the environmental factors such as increased competition. A respondent stated that a lack of funding, particularly for small farmers, is a significant concern for them (Interview, 20 October 2023). The farmers also consider the cost of maintenance of the technology, which may be prohibitive. One of the respondents stated that maintenance of some of the packhouse equipment is the responsibility of the supplier, but software upgrading costs money, so it is not always done if not necessary (Interview, 11 October 2023). It is for this reason that the types of automation outlined in this section are mainly utilised by large commercial farmers whose main market is the export market.

Another key consideration for some farmers is whether the technology can be utilised across different farm operations. If a technology is only for a specific function, it may not be an efficient use of funds to purchase it rather than one that can be used for various functions. This is especially the case when (particularly) smaller farmers receive funding from the government (Interview, 20 October 2023). Thus, organisational factors related to economies of scale, as highlighted by Na et al. (2023), also play a significant role in the decision to adopt certain advanced technologies.

Based on the analysis, it seems that post-harvest technology in the citrus industry has advanced more than pre-harvest and harvest technology. A respondent stated that the growing of the fruit can be automated to a certain extent. However, there is a high level of precision and care that is needed with fruit compared to other products, such as cereals or sugarcane, of which the appearance is not important. A respondent noted that there is almost no automation in the harvest stage because each fruit must be picked individually and with extreme care to make sure that it does not get any marks on it that would lead to the customers not wanting to buy it (Interview, 12 October 2023). It is worth noting that, although some of the automation technology, especially in the packhouse, is not necessarily new, it has still advanced significantly, particularly in the last five to 10 years.

The next section analyses the effects of and constraints on the use of advanced technology in the citrus farming.

5.2 Constraints on and Effects of the Use of Advanced Technology in Citrus Farming

We analysed technology adoption obstacles on the basis of these different criteria and identified the following constraints on advanced technology adoption:

One of the farm management systems used by citrus growers is 'FarmNode' software, which consists of several modules enabling users to scout pests and store the related data, use sensors and soil moisture probes to regulate the irrigation system, as well as manage the dosage of pesticides and fertilisers (Interview, 14 August 2023). The profitability of this system is largely dependent on scale economies, with larger commercial firms being able to adopt it, while many small-scale farmers find its implementation cost and management system prohibitive (Interview, 13 October 2023).

This technology is developed in South Africa and may be easily observable by potential adopters, but the digital network infrastructure to enable it is not always available in the remote areas and in valleys where the citrus plantations are located. In these locations, the 4G coverage is still deficient and no alternative digital data-transmission infrastructure is available (Interview, 13 October 2023). The defective electricity supply by the state-owned power utility Eskom, which results in frequent power blackouts, adds further complications to the utilisation and maintenance of the system, as the constant loss of power load affects the related equipment and the data transmission infrastructure even when it is available. Some of the organisational characteristics, such as managerial attitudes and technical skills of employees, do not seem to constitute significant constraints, as most managers interviewed for this study indicated a general positive attitude towards innovation and technology adoption, along with readiness to invest in skills training of employees to match the needed skills requirements. However, for some complex technological systems requiring external skills, the immigration policies put in place by the Department of Home Affairs (DHA) are perceived to constitute a significant obstacle to the recruitment of foreign skilled employees. Most interview respondents reported having positive working relations with the Department of Agriculture, Land Reform and Rural Development (DALRRD)[1] and tended to appreciate its supportive role in providing them with solutions to the electricity supply crisis. This is done because the government considers the agricultural sector one of its strategic priorities.[2] Technology adoption usually carries the risk of employment displacement, and the potential effects are of particular concern to South Africa, where the unemployment rate is the highest in the world (Magome, 2023).

Access to finance does not appear to constitute a major obstacle for larger companies, but for smallholder farmers lacking appropriate collateral it remains a significant factor limiting their ability to adopt advanced technologies. For example, the Citrus Growers Association has estimated that only approximately 25% of small-scale black farmers affiliated to the Grower Development Company are actively adopting precision agriculture technologies. As a consequence, the DAFF and the Citrus Growers Association collaborate in a programme providing agricultural extension services and facilitating access to finance by smallholder black farmers. These farmers constitute the majority of historically disadvantaged producers and have a lower likelihood of obtaining the necessary collateral for commercial lending (Interview, 20 October 2023). For this purpose, the minister has established an Agro-Fund to help farmers access the funding needed to face the energy crisis and finance technology acquisition where applicable (Interview, 20 October 2023).

The pressure from regulators, far from being an obstacle, provides an incentive to adopt technologies that help reduce the usage of pesticides and fertilisers, in accordance with the country's environment sustainability objectives.

Regarding the effects of technology adoption on skills and employment, cost and wastage reduction, higher efficiency in quality control, skills upgrade, employment preservation and sustainability of production are the main outcomes observed by respondents.

The observed cost reduction generated by the use of fully automated system in packhouses comes from the increase in the accuracy of quality control, which allows the packhouse to treat larger volumes during the so-called normal picking season. The increase in precision of the fruit grading system enables the packhouse to better plan the packing and avoid

[1] At the time of writing, the government department was named the Department of Agriculture, Land Reform and Rural Development. Since then, the department has been split into two – Agriculture, and Land Reform and Rural Development.

[2] On 12 May 2022, the then Minister of Agriculture, Land Reform and Rural Development launched the Agriculture and Agroprocessing Master Plan, which put the agricultural sector among the main strategic pillars of the country's recovery and reconstruction in the post-COVID 19 period.

overmaturation of the fruits during the picking season. It therefore saves labour inputs without shedding employment, enables farmers to reduce the loss due to wastage by concentrating the packing in a shorter picking period, and makes it easier to grade the fruits in precise categories with specific requirements for export markets in terms of sizes and colour description (no blemishes). The automated system also enables the packhouse to save on the handling space in comparison to what a manual system would require. Employment shedding is avoided because the limiting factor is rather the volume that can be treated every day. Human labour therefore operates in complementarity with the automated systems.

> We don't have less people, but we're packing more fruit … We still have 60 to 70 people working in the packhouse, but we are packing 200 tons where we used to pack 100 tons per day (Interview, 12 October 2023).

Technology adoption also results in shifts in technical skills, whereby many manual tasks are taken over by automated systems and personnel move to tasks using technology to produce more and expand production.

> So, it takes the manual terrible jobs out of the system and people can more focus on managing and doing quality checks and so on. So, there, I think technology has really changed the game. So yeah, that is definitely a big part of the business that is, and it's becoming more automated every year (Interview, 12 October 2023).

Mindful of the high unemployment pressure, respondents indicated that the introduction of new technologies goes together with production extension and upskilling or reskilling, rather than employment loss.

> From pretty low management [level], we require everyone to be at least computer literate. Everything is being done on the computer. We are trying to not have any paperwork anymore. Communication skills need to be good. I mean, we're having these meetings (Interview, 12 October 2023).

The use of sensors and software such as 'FarmNode' in the management of a nursery within a controlled environment enables growers to produce high-quality trees all year round and reduce losses due to freezing. The result is higher productivity overall. The adoption of precision agriculture technologies also has implications for the sustainability of the agricultural production processes: by facilitating the scouting and tracking systems that enable the targeted and optimised use of irrigation, pesticides and fertilisers, the use of software such as the 'FarmNode' leads to considerable savings in water usage (up to 24% of irrigation water in comparison to traditional irrigation systems) and a considerable reduction in pesticide use (Interview, 12 October 2023). The use of automatic systems also enables the storage of information on the production process, which enable the connected retailer more easily to assess the sustainability of the production methods and respond to queries by consumers.[3]

6. Discussion

The observed patterns of agriculture technology adoption in various sub-sectors in South Africa reflect the dynamics of various technological, organisational and environmental factors within each sub-sector, in close alignment with the main observations highlighted by Pierpaoli et al. (2013). Perceived usefulness, economies of scale (as related to farm size), management attitude, complementary technological infrastructure and access to finance play an important role in enabling precision agriculture technologies, while market requirements and harvest optimisation appear to be key drivers of the use of automation technology in citrus packhouses. Increasing crop output and profit optimisation indeed remain at the heart of commercial farming, and the decision to adopt precision agriculture technologies comes in support of this goal (Barnes et al. 2019; Kolady et al. 2021). The involved economies of scale and the adoption challenges faced by smallholder farmers (especially digital platform access and high data costs) underscores the importance of coordinated policy and the role of affordable complementary infrastructure in fostering inclusive technology diffusion, as argued by Aguera et al. (2020) and Kudama et al. (2021).

The deployed technologies, rather than being disruptive, seem to strengthen the performance of the industry in its existing markets and is supported by compatible infrastructure, as well as a favourable institutional setting. The deployment of a locally developed digital agriculture technology provides the South African citrus sub-sectors with the advantage of technological tools directly adapted to their needs and appropriate for the intended tasks. It also provides its users with certain levels of autonomy, in contrast to the type of dependence on powerful foreign technology platforms that often dominate the smartification of agriculture (Krishan et al. 2021; Maschewski and Nosthoff 2022). Easy access to a certain technology is also a good predictor of its adoption and potential diffusion, as observed by Gabriel and Gandorfer (2023) in the case of digital technology adoption among farmers in Bavaria.

The adoption patterns that were inferred from the interview responses confirm the role of perceived usefulness and relative advantage in the adoption of precision agriculture technologies (Kolady et al. 2021; Pierpaoli et al. 2013). When it comes to the perceived ease of use, it is of particular importance to bear in mind the distinction between precision agriculture technologies with mostly embodied technological knowledge and those that are information intensive. Information-intensive technologies require additional skills to optimise

[3] The interviewed respondents do not deal directly with the consumers in communicating the production processes, but they discuss the consumer sustainability preferences through connected retailers.

their application and usefulness, while embodied precision agriculture technology embeds most of its functions as automatic, thereby requiring less effort in utilisation. The latter are therefore more easily adopted (Kolady et al. 2021; Miller et al. 2019; Pierpaoli et al. 2013). Policies aimed at fostering the inclusive adoption and diffusion of precision agriculture technologies will need to factor all these findings into their deliberations, and align them with long-term strategic objectives.

7. Concluding Summary

This study has explored the dynamics of 4IR technology adoption in the agricultural sector in South Africa, with particular focus on the citrus sub-sector.

The analysis focused on drivers and enablers of and obstacles to adoption, as well as the effects of the diffusion of these technologies on skills demand, on employment and on the adopting firm's performance.

The analysis of qualitative data collected from farmers, farmers' associations and agricultural technology service providers indicates a sophisticated use of advanced technologies by the citrus sub-sector, especially as an optimisation strategy responding to the high-quality requirements of its export market. The use of imagery and sensors, as well as the exploitation of big data analytics in crop growth and fruit packhouses, characterises the citrus export industry and enables it to conduct its operations efficiently and to command a premium quality market image around the world.

The use of a specialised system with various customised application modules enables the industry to regulate irrigation, fertilisation, pest control and pruning, as well as to access agricultural services, supplies and market information. Because of the high cost involved in adopting many of the advanced technologies focused on in this study, economies of scale play an important role in the decision to adopt, with larger farms (more than 500 ha) being the ones most likely to use the most advanced technologies. As can be expected, many small-scale farmers are finding these technologies prohibitively expensive so that the coordination of their resources through industry associations and government support remain essential to broadening their chance to access the technologies. Smooth collaboration with a competent government department, namely the then DALRRD, was perceived by respondents as having created favourable conditions for the large players in the industry to thrive and contribute to the country's economic dynamism.

These findings also highlight the importance of fostering digital inclusion among farmers as a measure to increasing their visibility in the wider value chain (see also Aguera et al. 2020; Kudama et al. 2021). Access to digital infrastructure networks being one of the limiting factors, policies aimed at strengthening the diffusion of advanced technologies in the sector should focus on improving the coverage and affordability of such infrastructure throughout the country, as well as supporting digital skills training and capacity building among prospective adopters. The problem of affordability of some advanced technologies, such as the use of drones and satellite imagery mentioned by some respondents, implies that policy coordination and land reform acceleration are necessary to ensure that more producers reach the level of scale and skills that enable them to make profitable use of such technologies. Such support should ideally give priority to smallholder farmers, including through the development of shared technology services that help them overcome the constraints of scale that render outright purchase of technologies prohibitively costly.

Access to and utilisation of digital technologies are not without risks, especially when part of the technology services is in the hands of powerful private corporations handling a multitude of data, including proprietary data generated through technology utilisation. Data protection needs to be central to technology use, and adequate regulations have to be put in place to protect small-scale farmers from the related vulnerabilities when they choose to adopt digital technologies connected to private platforms. The development of alternative technology support services with the necessary adherence to local regulations could be explored to improve the position of technology users. The role of the Departments of Agriculture and of Land Reform and Rural Development is widely seen as promotive by most respondents: additional reforms intended to increase access to land by smallholder farmers should be accelerated to ensure that more large-scale farms are created by members of the previously disadvantaged population groups so that access to finance and advanced technology becomes an economically viable option.

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